AN IMPROVEMENT IN OBJECTIVES.

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Eight years ago I presented to the American Association for the Advancement of Science a description of a new quadruple objective for astronomical telescopes. The general acknowledgment with which the paper was received, and the high estimation of the theoretical principles of the invention, by scientific authorities of this country as well as Europe, encourage me to present to this Society a description of another improvement in objectives, which I expect will be of equal value for both the telescope and the microscope. Although I have, unfortunately, not had sufficient opportunity for properly executing an objective of the above mentioned description, and thus practically demonstrating its advantages, I must confess that during the time I have become conscious of a practical defect, which is the increased number of lenses. I am now of the opinion that any improvement of objectives which requires additional lenses will always be objectionable, however valuable the improvement may otherwise be. The objective which I now wish to describe is free from this defect. It consists of two lenses only; one of crown- and one of flint-glass, like the ordinary objective. But the formula is based upon a new principle. In my description of the quadruple objective, I have spoken of the so-called aberrations of higher order. Let me briefly review this for the better understanding of the following description.

We know that the flint-glass lens of an objective acts merely as a corrector of both the spherical and chromatic aberrations of the crown-glass lens; but, owing to this double action, the said correction is, even in its best possible form, imperfect, in so far as, when the part or zone lying about midway between the center and the

periphery is just right in correction, then the central part leaves a small remnant uncorrected, while the peripheric zone is already over corrected. These unremovable remnants or so-called aberrations of higher order are the only cause of those imperfections of the achromatic objective which are dependent on the figure or curvature of the lens, and, therefore, the best formula for an objective will be that by which these aberrations are mostly reduced.

Since the discovery of achromatism nothing has been spared to find, by the aid of mathematics, the best possible form for the flint-glass lens for the correction of the aberrations of the crown-glass lens; but, for the finding of the proper form or to better the proportion of curvatures of the crown-glass lens itself, there never was a special rule adopted or theoretical law found by which to obtain the most favorable result. But the calculations were based upon the principle that for any positive crown-glass lens a negative flint-glass lens can be found, combined with which it will form an achromatic objective in the common sense, and according to this principle no special pains were taken to find the proper form of the crown-glass lens.

My object in this paper is to show that for the best possible construction of an achromatic objective the proper figure or proportion of curvatures of the crown-glass lens is an important factor, submitted to a positive theoretical law, and that, as a consequence of the neglect of this law, the present objective is far from having the best possible form. The angular aperture, or, in other words, the proportion of aperture to focal distance of an objective, is limited by the spherical aberration of the crown-glass lens, because the latter greatly increases with the increase of the angular aperture, and consequently the aberrations of the higher order are increased. But this limit can be extended if the spherical aberration of the crown-glass lens can be, without change of focal length and diameter, reduced by a mere change of curvature, because this reduction involves a corresponding reduction of the aberrations of higher order. According to this we can imagine two achromatic objectives which are equal in focal distance and aperture, but although the flint-glass lens of both have the best possible form for correction of the aberrations of their respective crown-glass lens, one of the

lenses is superior to the other in the correction of the aberrations of higher order, because the spherical aberration of the crown-glass lens is less than that of the other.

We now arrive at the question whether the spherical aberration of the crown-glass lens of the present achromatic objective can be reduced by a mere change of proportion of curvature, and if so, what is the theoretical law after which this proportion must be found? This law, which I have found by careful study, may be expressed as follows: *The spherical aberration of a lens for rays of given direction will be a minimum if the proportion of the curvatures of the refracting surfaces is such by which the angle of refraction of the medium ray at the entering surface is equal to that at the emerging; or, in other words, by which the angle of the perpendicular inclination of the medium ray at the entering surface is equal to that of the emerging surface.* If the rays entering a lens are parallel, or nearly so, as is the case with the telescope, then they will, after having passed through the lens, be changed by refraction to a converging direction toward the focal point of the lens; and to be equal in perpendicular inclination upon their respective surfaces, the entering or first surface will certainly have to be of correspondingly shorter curvature than the emerging or second surface. For a lens of a relative focus and diameter, as the crown-glass lens of the present telescope, the radius of the curvature of the inner surface will have to be about twice as long as that of the outer surface, to fulfill the condition of minimum spherical aberration. But we are familiar enough with the construction of our present objective to admit that just the contrary is the case; that is, the curvature of the outer surface of the crown-glass lens is by far the longest. If the crown-glass lens is reversed so that the inner or shorter curved surface is brought outside toward the parallel rays of the object, then the form of the lens would much nearer fulfill the condition of minimum spherical aberration. But then, of course, the flint-glass lens will no longer have the proper form as a correcting lens; it would now over-correct the spherical aberration of the crown-glass lens, and, therefore, a more flat, long curved form of the same would be required.

If the exact form or curvature of minimum aberration of the

crown-glass lens, as well as that of the correcting flint-glass lens, as found by calculation, is compared with the present objective, it will be found that the aberrations of higher order in the new objective are reduced to about one-third of the old one, and a corresponding gain in the definition and reduction of color; or otherwise an extension of the limit of aperture must be the result. Let me, right here, mention another idea as a further step for improvement of the objective in the same direction as described ; that is, a further reduction of the aberrations of higher order.

I have in my foregoing description given the law after which a lens of minimum spherical aberration for rays of a *given* direction has to be constructed, and I will here complete this law by adding, that *the absolute minimum of spherical aberration of a lens is obtained, if the refracting surfaces of the same are equal in curvature, and the rays entering the lens are coming from a certain point of the optical axis, being in distance from the lens a little over twice that of its nominal focus, thus meeting at the other side at an equal distance and forming a cone equal to that at the entering side.* Now there is a simple way to give the rays, coming from a distant point or object, before entering the crown-glass lens of the telescope, a direction which will be nearly adequate to the first mentioned condition; namely, if the flint-glass lens is placed in front of the crown-glass lens. The parallel direction of the rays will then, by the negative flint-glass lens, be changed into such diverging direction as would correspond with a cone, being only a little shorter than that required for an equal-sided crown-glass lens, and the latter will then for minimum spherical aberration have to be very near equal-sided, thus allowing the aberration of higher order to be in higher degree reduced than in the before described objective. But, however, as an objection to this arrangement, it may be mentioned that the flint-glass lens will be directly exposed to the external air and liable to oxidation.

In my foregoing description I have, for the purpose of avoiding complications and giving a clearer understanding, referred to the telescope only, but as the construction of this instrument is submitted to the same theoretical laws as that of the microscope, little remains to be said about the application of the

described new principle to the microscope. Our present microscope objectives are all achromatic in the common sense, but they differ widely in angular aperture, and accordingly in definition and resolving power. But the angular aperture is dependent on the correction of the aberrations of higher order, the latter again on the spherical aberrations of the crown-glass lenses of the system. If the crown-glass lenses are transformed according to the described principle and law of minimum spherical aberration, and then the flint-glass lenses so changed as to properly correct the aberrations of the crown-glass lenses, the same result will be obtained as with the telescope objective. The extension of the limit of angular aperture will admit of giving the low power objective, with long working distance, a definition and quantity of light which at present are united only in considerably higher powers of short working distance.